

# Measuring the Higgs boson couplings

Michael Rauch

*Institut für Theoretische Physik, Universität Karlsruhe,  
Karlsruhe Institute of Technology, 76128 Karlsruhe, Germany*

Once a Higgs boson has been discovered, it is also important to know what are its properties, in particular its couplings to the other particles. At the LHC, there will be many observable channels that can be used to measure the relevant parameters. Using the SFitter framework, we project these measurements onto a weak-scale effective theory with general Higgs boson couplings. Thereby, our analysis profits from the error treatment and the parameter determination tools already used for new-physics searches. We use this to study both the individual couplings and their associated errors as well as correlations between them.

## 1 Introduction

Understanding the mechanism of electro-weak symmetry breaking is one of the main goals of the LHC. In the Standard Model (SM), this is achieved by the Higgs field, an  $SU(2)$  doublet, which obtains a vacuum expectation value (vev) <sup>1,2</sup>. Three degrees of freedom of this Higgs field are absorbed by the  $W$  and  $Z$  gauge bosons and form their longitudinal modes, while the remaining one becomes a scalar, the Higgs boson. The kinetic terms of the Higgs field in the Lagrangian lead to  $WWHH$  and  $ZZHH$  interactions. Interactions with fermions are added via Yukawa-type couplings. Once the Higgs is replaced by its vev in these expressions, we obtain the mass terms for gauge bosons and fermions. Consequently, the couplings of the Higgs to the other particles are not free parameters, but proportional to the known masses and the vev.

The only remaining unknown parameter in the SM is the mass of the Higgs boson. A lower bound of 114.4 GeV is given by the direct searches from LEP <sup>3</sup>, with the latest Tevatron results approaching a similar sensitivity <sup>4</sup> in this region. Results from the LHC <sup>5,6</sup> indicate an upper limit of 145 GeV. Higgs boson masses above 200 GeV, where allowed regions from direct searches are still left, are strongly disfavoured by electro-weak precision data <sup>7</sup>. As the Higgs couplings in the SM are completely determined by the known masses, we can use this theoretical prediction and compare it <sup>8,9,10,11</sup> with future LHC measurements of Higgs boson channels <sup>12</sup>. For this we assume that the discrete quantum numbers, like CP structure or spin <sup>13</sup>, are identical to the SM value. There are many models where deviations of the couplings can occur. This includes simple extensions like a second Higgs doublet, as for example in supersymmetry <sup>14</sup> or also in Higgs portal models <sup>15</sup>, or composite models <sup>16</sup>, where in a strongly-interacting sector the Higgs emerges as a pseudo-Goldstone boson.

For this task it is crucial to correctly account for the different types of errors. As events are counted these statistical errors are of Poisson type. Systematic errors are correlated between different measurements and we need to include the full correlation matrix. The best description for theory errors is the RFit scheme <sup>17</sup>, which takes them as box-shaped. The SFitter tool <sup>18</sup>

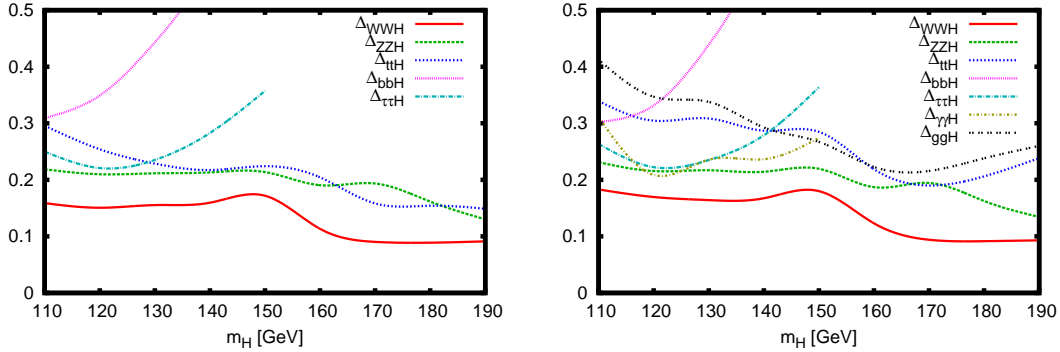


Figure 1: Error on the Higgs-boson couplings as a function of the Higgs mass without (*left*) and including (*right*) additional dimension-five operators for the 14 TeV LHC with 30 fb<sup>-1</sup> and SM couplings.

allows us to construct a fully-dimensional log-likelihood map of the parameter space. To reduce this into plottable one- or two-dimensional distributions, both Bayesian (marginalisation) and Frequentist (profile likelihood) techniques are available.

## 2 Calculational setup

As the underlying model we assume the SM with a generalised Higgs sector, where the Higgs couplings can take arbitrary values. They are parametrised in the following way: For all particles  $j$  with tree-level couplings to the Higgs, the coupling is modified to

$$g_{jjH} \rightarrow g_{jjH}^{\text{SM}}(1 + \Delta_{jjH}) . \quad (1)$$

Additionally, there are two important loop-induced couplings, namely those to photons and gluons. When altering the tree-level couplings, these will change as well. Additionally, we can introduce dimension-five contributions, which originate from new particles running in the loop, e.g. the supersymmetric partners in SUSY models. Hence, these couplings are modified according to

$$g_{jjH} \rightarrow g_{jjH}^{\text{SM}}(1 + \Delta_{jjH}^{\text{SM}} + \Delta_{jjH}) , \quad (2)$$

where  $\Delta_{jjH}^{\text{SM}}$  denotes the contribution from modified tree-level couplings and  $\Delta_{jjH}$  the additional dimension-five part. We also take the masses of the top and bottom quark and the Higgs boson as free parameters, as they have, or will have, significant experimental errors. The total width of the Higgs boson is taken as the sum over all SM particle partial widths.

The LHC measurement channels which enter our analysis are derived from an ATLAS simulation and assume an integrated luminosity of 30 fb<sup>-1</sup> at a centre-of-mass energy of 14 TeV<sup>9,19</sup>. We then smear the simulated experimental results in 10000 toy experiments and fit the resulting Higgs couplings. From the distribution we can then read off the errors on the determination. More details on the setup and the procedure can be found in Ref.<sup>9</sup>.

## 3 Results

In Fig. 1 we present the results of our analysis. We show the 68% CL errors on  $\Delta_{jjH}$  for the different couplings. As input we take the expected measurements at the given Higgs mass assuming SM coupling strength. For other central values of the coupling, the difference on the errors is small. On the left-hand side we have neglected any contribution from additional dimension-five operators to the effective couplings, while on the right-hand side these are included as well. In both cases the  $WWH$  coupling is the best determined one, with an error ranging from 10 to 20 %. The region around 150 GeV is thereby the most difficult, because the rates for processes

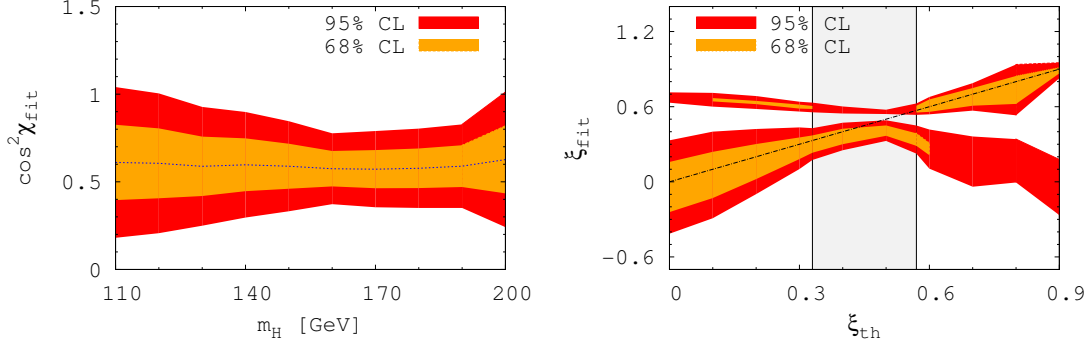


Figure 2: Obtainable precision of the fitted parameter at the LHC with 14 TeV and  $30 \text{ fb}^{-1}$ . *Left:* Higgs portal model with input value  $\cos^2 \chi_{\text{th}} = 0.6$ . *Right:* SILH model MCHM 5 at  $m_H = 120 \text{ GeV}$ . Both figures from Ref. <sup>10</sup>.

with Higgs decays into bottom quarks are already small and make these measurements difficult, as can be seen from the error on  $\Delta_{bbH}$ . Nevertheless it is still large enough to give a significant contribution to the total width, thereby influencing the branching ratios to all other particles. A large difference between the plots occurs for the top-quark Yukawa coupling. Without the additional contributions, this is mainly determined by its dominant role in gluon-fusion Higgs production. Including it, a shift can always be compensated by a corresponding contribution of the dimension-five operator. Only the channels with top-quark associated Higgs production can determine the size of the  $ttH$  coupling.

Once we go to new-physics models, the size of the Higgs couplings, which is predicted by the theory, can differ from the SM value <sup>10</sup>. Here, we shortly discuss two different models, the Higgs portal <sup>15</sup> and a strongly-interacting light Higgs (SILH) <sup>16</sup>. In the first model, an additional hidden sector is added, which is a singlet under the SM gauge groups. The only possible connection to the SM is via a quartic coupling  $\mathcal{L} \propto \Phi_s^\dagger \Phi_s \Phi_h^\dagger \Phi_h$  of the SM Higgs  $\Phi_s$  and the hidden sector Higgs field  $\Phi_h$ . This induces a mixing between the two Higgs particles, reducing the coupling between Higgs and SM particles by a factor  $\cos \chi$ . Additionally, decays of the Higgs into hidden sector particles appear if they are kinematically allowed, and lead to invisible Higgs decays. This leads to simple one-parameter fits such as the one shown in Fig. 2 on the left. Here we show for a theory input of  $\cos^2 \chi_{\text{th}} = 0.6$  and  $\Gamma_{\text{hid}} = 0$  the resulting fit for  $\cos^2 \chi$  as a function of the Higgs mass, assuming  $30 \text{ fb}^{-1}$  collected at 14 TeV. We see that in this scenario the SM ( $\cos^2 \chi = 1$ ) can be excluded at the 95% CL over the whole mass range.

In the SILH model, the Higgs emerges as a pseudo-Goldstone boson of a new strongly-interacting sector. The modifications of the couplings are parametrised by  $\xi = (\frac{v}{f})^2$ , where  $f$  is the Goldstone scale. This model also predicts significant deviations for Higgs pair production, which we do not consider in this analysis <sup>20</sup>. In the so-called MCHM4 scenario all Higgs couplings scale as  $\sqrt{1-\xi}$ , so we can take the previous results by identifying  $\cos^2 \xi = 1 - \xi$  and setting invisible decays to zero. In the MCHM5 scenario, the vector-boson Higgs couplings are modified as above, but the fermion couplings receive the factor  $\frac{1-2\xi}{\sqrt{1-\xi}}$ . This leads to interesting coupling structures, as the fermion couplings vanish for  $\xi = 0.5$  and rise again for smaller values with opposite sign. On the right side of Fig. 2 we show the results for the fitted value of  $\xi$  over the theory input. We see that for each input value two solutions emerge. For example, in the gluon fusion channel with Higgs decays into photons, for each theory value of  $\xi$  there are two possible fitted solutions that give the same rate. For vector-boson-associated production with decays into bottom quarks using subjet techniques <sup>21</sup>, another important channel, multiple solutions only exist for values of  $\xi \gtrsim 0.4$ . Therefore, this degeneracy is not a true one, but is induced by statistical fluctuations in the measurements. Each of the smeared toy experiments has a unique solution, but whether it is the correct one can only be resolved by higher integrated luminosities.

## Acknowledgements

We would like to thank the organisers of the “23rd Rencontres de Blois 2011” for the inspiring atmosphere during the workshop. This research was supported by the Deutsche Forschungsgemeinschaft via the SFB/TR-9 “Computational Particle Physics” and the Initiative and Networking Fund of the Helmholtz Association, contract HA-101 (“Physics at the Terascale”).

## References

1. P. W. Higgs, Phys. Lett. **12**, 132 (1964); P. W. Higgs, Phys. Rev. Lett. **13**, 508 (1964); F. Englert and R. Brout, Phys. Rev. Lett. **13**, 321 (1964).
2. A. Djouadi, Phys. Rept. **457**, 1 (2008) [arXiv:hep-ph/0503172]. V. Büscher and K. Jakobs, Int. J. Mod. Phys. A **20**, 2523 (2005); [arXiv:hep-ph/0504099]. D. Rainwater, arXiv:hep-ph/0702124.
3. [LEP, Tevatron and SLD Collaborations and Working Groups], arXiv:0811.4682 [hep-ex].
4. CDF, D0 and Higgs Working Group Collaborations, [arXiv:1107.5518 [hep-ex]].
5. ATLAS Collaboration, ATLAS-CONF-2011-135.
6. CMS Collaboration, CMS-PAS-HIG-11-022.
7. H. Flacher, M. Goebel, J. Haller, A. Hocker, K. Monig, J. Stelzer, Eur. Phys. J. **C60**, 543-583 (2009). [arXiv:0811.0009 [hep-ph]], M. Baak, M. Goebel, J. Haller, A. Hoecker, D. Ludwig, K. Moenig, M. Schott, J. Stelzer, [arXiv:1107.0975 [hep-ph]].
8. M. Dührssen, S. Heinemeyer, H. Logan, D. Rainwater, G. Weiglein and D. Zeppenfeld, Phys. Rev. D **70**, 113009 (2004).
9. R. Lafaye, T. Plehn, M. Rauch, D. Zerwas and M. Dührssen, JHEP **0908**, 009 (2009) [arXiv:0904.3866 [hep-ph]], M. Rauch [SFitter Collaboration], [arXiv:1005.2843 [hep-ph]].
10. S. Bock, R. Lafaye, T. Plehn, M. Rauch, D. Zerwas, P. M. Zerwas, Phys. Lett. **B694**, 44-53 (2010). [arXiv:1007.2645 [hep-ph]].
11. F. Bonnet, M. B. Gavela, T. Ota, W. Winter, [arXiv:1105.5140 [hep-ph]].
12. G. Aad *et al.* [The ATLAS Collaboration], arXiv:0901.0512 [hep-ex], G. L. Bayatian *et al.* [CMS Collaboration], J. Phys. G **34**, 995 (2007).
13. J. R. Dell’Aquila and C. A. Nelson, Phys. Rev. D **33**, 93 (1986).; T. Plehn, D. Rainwater and D. Zeppenfeld, Phys. Rev. Lett. **88**, 051801 (2002); C. P. Buszello, I. Fleck, P. Marquard and J. J. van der Bij, Eur. Phys. J. C **32**, 209 (2004); V. Hankele, G. Klamke, D. Zeppenfeld and T. Figy, Phys. Rev. D **74**, 095001 (2006); C. Ruwiedel, N. Wermes and M. Schumacher, Eur. Phys. J. C **51**, 385 (2007).
14. for an introduction see e.g. S. P. Martin, arXiv:hep-ph/9709356; I. J. R. Aitchison, arXiv:hep-ph/0505105; J. F. Gunion and H. E. Haber, Phys. Rev. D **67**, 075019 (2003).
15. B. Patt, F. Wilczek, [hep-ph/0605188].
16. G. F. Giudice, C. Grojean, A. Pomarol, R. Rattazzi, JHEP **0706**, 045 (2007). [hep-ph/0703164], J. R. Espinosa, C. Grojean and M. Muhlleitner, JHEP **1005**, 065 (2010) arXiv:1003.3251 [hep-ph].
17. A. Hocker, H. Lacker, S. Laplace and F. Le Diberder, Eur. Phys. J. C **21**, 225 (2001); J. Charles *et al.* arXiv:hep-ph/0607246.
18. R. Lafaye, T. Plehn, M. Rauch and D. Zerwas, Eur. Phys. J. C **54**, 617 (2008); for earlier versions of SFitter see: R. Lafaye, T. Plehn and D. Zerwas, arXiv:hep-ph/0404282 and arXiv:hep-ph/0512028.
19. M. Dührssen, ATL-PHYS-2003-030.
20. R. Grober, M. Muhlleitner, JHEP **1106**, 020 (2011). [arXiv:1012.1562 [hep-ph]].
21. J. M. Butterworth, A. R. Davison, M. Rubin and G. P. Salam, Phys. Rev. Lett. **100**, 242001 (2008), ATLAS Collaboration, ATL-PHYS-PUB-2009-088.